



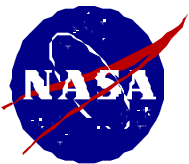
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Comparative Analysis of Phase Retrieval and Shack-Hartmann Wavefront Sensing Space Based Segmented Optical Control System

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Abstract

We present an ongoing study to compare various methods of **phase retrieval**, **phase diversity**, and **Shack-Hartmann** sensing for *fine figure control* of deployable segmented aperture space optical systems. We develop comprehensive models of an optical system, active optical bench, focal plane, phase retrieval algorithms, control algorithms and compare the various methods in a Monte-Carlo type fashion. The results will eventually be compared with actual results from a NASA testbed and flight missions.



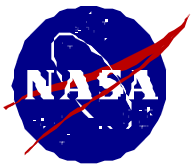
Viewgraphs will be available at <http://jansky.gsfc.nasa.gov/OSCAR>

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Study Goals and Methodology

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- **GOALS:**

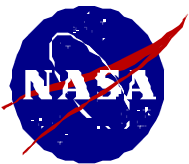
- “BEST” WFS / Optical Control or Segm’t Aper Space Telescopes.
- Develop / Verify hi-fidelity optical model of entire control process.
- model useful for many NASA projects.

- **“best” refers to:**

accuracy/precision, spatial frequency
image quality, dynamic range
robustness, computational complexity

- **Methodology**

- develop high fidelity computer model of entire control loop
OTA, active bench, focal plane, WFS, actuators, control alg.
- include effects of:
readnoise, darkcurrent noise, photon noise, sampling
polychromatism, jitter, sampling, pixelization, detector MTF
mid- and hi-spatial freq, micro-roughness, actuator influence
- cycle model in Monte-Carlo fashion, tabulate and compare results
- verify as “real” data becomes available
- update model

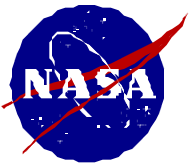


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Optical Modelling

- Initial Study “tuned” to Developmental Comparative Active Telescope Testbed (DCATT)
- includes:
 - Full-Aperture Zernikes /Sub-Aperture Zernikes, $\{0 - 2.5\lambda \text{ rms}\}$.
 - 90.3 cm aperture, 21% obscured, 7 hex segments.
 - Residual Polish Marks / Random power law surfs.
 - Polychromatic PSFs, $\{\lambda=0.6328 \text{ um}, \Delta\lambda=10\text{nm}\}$.
 - System Jitter, $\{0 - 1.5 \text{ pixels rms}\}$.
 - Pixelization $\{9 \text{ um pixels}\}$.
 - read noise $\{13 \text{ electrons rms}\}$.
 - photon noise.
 - full-well $\{80,000 \text{ e}\}$.
 - quantization $\{12 \text{ bit} = 4096\}$.
 - Actuator Influence functions (Xinetics 349 DM)
- Software developed on MasPar MP2 (16,384 procs / 6 GFLOPs)
- Currently being ported to C/MPI

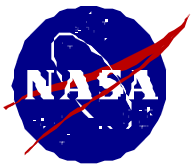




Example of LEO System Control File

Keywords for:

- Pupil diameters, wavelengths, bandpass,
- pixelization, obscuration ratio,
- full aperture Zernikes, spiders, pads,
- aper rotation with respect to CCD line/scan
- jitter in x and y directions,
- PM and SM secondary mirror mid-spatial
- random high spatial frequencies
- detector dynamic range, shot noise,
- readnoise, quantization, finite pixel size.
- actuator input files, influence functions



```
= aper_22.in
= 0.903
= 0.6328
= 0.1330311
= Y
= 0.1330311
Npsf= 7
fwhm= 0.0100
= 0.21384
Ztype= 1
Z01= -0.051605
Z02= 0.014292
Z03= 0.121884
Z04= 0.012207
Z05= 0.121851
Z06= 0.164621
Z07= 0.187863
Z08= 0.012174
Z09= -0.110907
Z10= -0.090205
Z11= -0.126233
Z12= 0.227831
Z13= 0.078349
Z14= -0.084945
.
Z32= -0.144799
= N
= N
= 0.000000
= 0.000000
= 1
= 0.000000
= 0.000000
= N
= N
= 0.0
= 0.0
= Y
= N
= N
= N
= 0.01
= 993
= act0.in
Nact= 349
act_cof= 39.8175
fullwell = 80000.0
shot = Y
readnoise = 13.0
quant = 4096.0
```

```
# Aperture control file (set to "none" if not using).
# Exit pupil Diameter (meters) (system is F/15)
# Wavelength (microns)
# Output Sample spacing (arseconds) (pixels are 9 um)
# Generate PRF (Y or N)
# Detector element size for PRF (arseconds)
# Number of PSF's across Passband.
# FWHM of Filter (microns) (if Npsf's > 1)
# aperture obscuration ratio (0.21384)
# Zernike type (0 = Annular, 1 = Code 5)
# Piston (microns WFE )
# X-tilt (microns WFE )
# Y-tilt (microns WFE )
# X-Y astigmatism (microns WFE )
# Focus (microns WFE )
# 45-degree (microns WFE )
# Trefoil (microns WFE )
# X-coma (microns WFE )
# Y-coma(microns WFE )
# Trefoil (microns WFE )
# (microns WFE )
# (microns WFE )
# Fourth-order spherical (microns WFE )
# (microns WFE )

# (microns WFE )
# Are OTA SMA spiders present? (Y or N)
# Are OTA PMA pads present? (Y or N)
# OTA aperture rotation angle (degrees)
# WF/PC aperture rotation angle (degrees)
# Computed PSF resampling factor (integer > 0)
# WF/PC aperture X-axis offset (pixels)
# WF/PC aperture Y-axis offset (pixels)
# Use PM surface map? (Y or N)
# Use SM surface map? (Y or N)
# x - Jitter (milli-arcseconds)
# y - Jitter (milli-arcseconds)
# Create phase map file ?(Y or N)
# Use Recovered Surface Map (Y/N/P),if Y or P then PM=SM=N.
# Apodized the Pupil function ? (Y or N)
# Add in random Gaussian surface (Y or N)
# S. Dev. of random Gaussian surface (microns).
# integer seed value for random surface generator.
# Actuator file ("none" if not using)(units are um WFE).
# Total number actuators in pupil.
# R(r) = exp(-act_cof*r)*sin(act_cof*r+PI/4)
# Detector fullwell in electrons.
# Add in shot noise (Y/N).
# Detector readnoise in electrons.
# number of quantize levels (4096 levels, 0=>not quantize).
```

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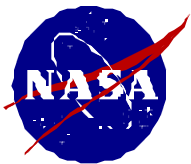
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Example of Section of LEO Aperture Control File

Keywords for:

- POLY => regular polygon apertures
- TRIA => triangular apertures
- RECT => rectangular apertures
- CIRC => circular apertures
- each aperture can have its own Zernikes,
or can AND'ed with other sub-aps to form
a segment.
- Each set of Zernikes can have its own
center and normalization radius.



```
POLY = 1 {
  Nsides = 6           # Number of sides of polygon
  radius = 0.173205    # radius of inscribed polygon (meters)
  xcent = 0.000000     # X-center of polygon (meters)
  ycent = 0.000000     # Y-center of polygon (meters)
  theta = 0.000000     # rotation angle of polygon (degrees)
  piston = 0.000000    # piston error (microns-surface error)
  xtilt = 0.000000     # tilt of mirror in x-direction (arcsec)
  ytilt = 0.000000     # tilt of mirror in y-direction (arcsec)
  Z01 = -0.041284      # Piston (microns WFE )
  Z02 = 0.011433       # X-tilt (microns WFE )
  Z03 = 0.097507       # Y-tilt (microns WFE )
  Z04 = 0.009765       # X-Y astigmatism (microns WFE )
  Z05 = 0.097481       # Focus (microns WFE )
  Z06 = 0.131696       # 45-degree astigmatism (microns WFE )
  Z07 = 0.150290       # Trefoil (microns WFE )
  Z08 = 0.009740       # X-coma (microns WFE )
  Z09 = -0.088725      # Y-coma (microns WFE )
  Z10 = -0.072165      # Trefoil (microns WFE )
  Z11 = -0.100985      # (microns WFE )
  Z12 = 0.182264       # (microns WFE )
  Z13 = 0.062679       # Fourth-order spherical (microns WFE )
  apodize = N          # anti-alias mask (Y/N).
}
```

```
POLY = 2 {
  Nsides = 6           # Number of sides of polygon
  radius = 0.173205    # radius of inscribed polygon (meters)
  xcent = 0.000000     # X-center of polygon (meters)
  ycent = -0.306000    # Y-center of polygon (meters)
  theta = 0.000000     # rotation angle of polygon (degrees)
  piston = 0.000000    # piston error (microns-surface error)
  xtilt = 0.000000     # tilt of mirror in x-direction (arcsec)
  ytilt = 0.000000     # tilt of mirror in y-direction (arcsec)
  Z01 = -0.115865      # Piston (microns WFE )
  Z02 = 0.044346       # X-tilt (microns WFE )
  Z03 = -0.110537      # Y-tilt (microns WFE )
  Z04 = 0.020632       # X-Y astigmatism (microns WFE )
  Z05 = 0.043695       # Focus (microns WFE )
  Z06 = 0.113846       # 45-degree astigmatism (microns WFE )
  Z07 = 0.157808       # Trefoil (microns WFE )
  Z08 = 0.087005       # X-coma (microns WFE )
  Z09 = 0.209875       # Y-coma (microns WFE )
  Z10 = -0.004463      # Trefoil (microns WFE )
  Z11 = -0.097702      # (microns WFE )
  Z12 = -0.120061      # (microns WFE )
  Z13 = -0.013088      # Fourth-order spherical (microns WFE )
  apodize = N          # anti-alias mask (Y/N).
}
```

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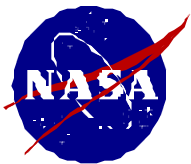
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Optical Modeling

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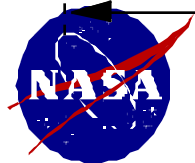
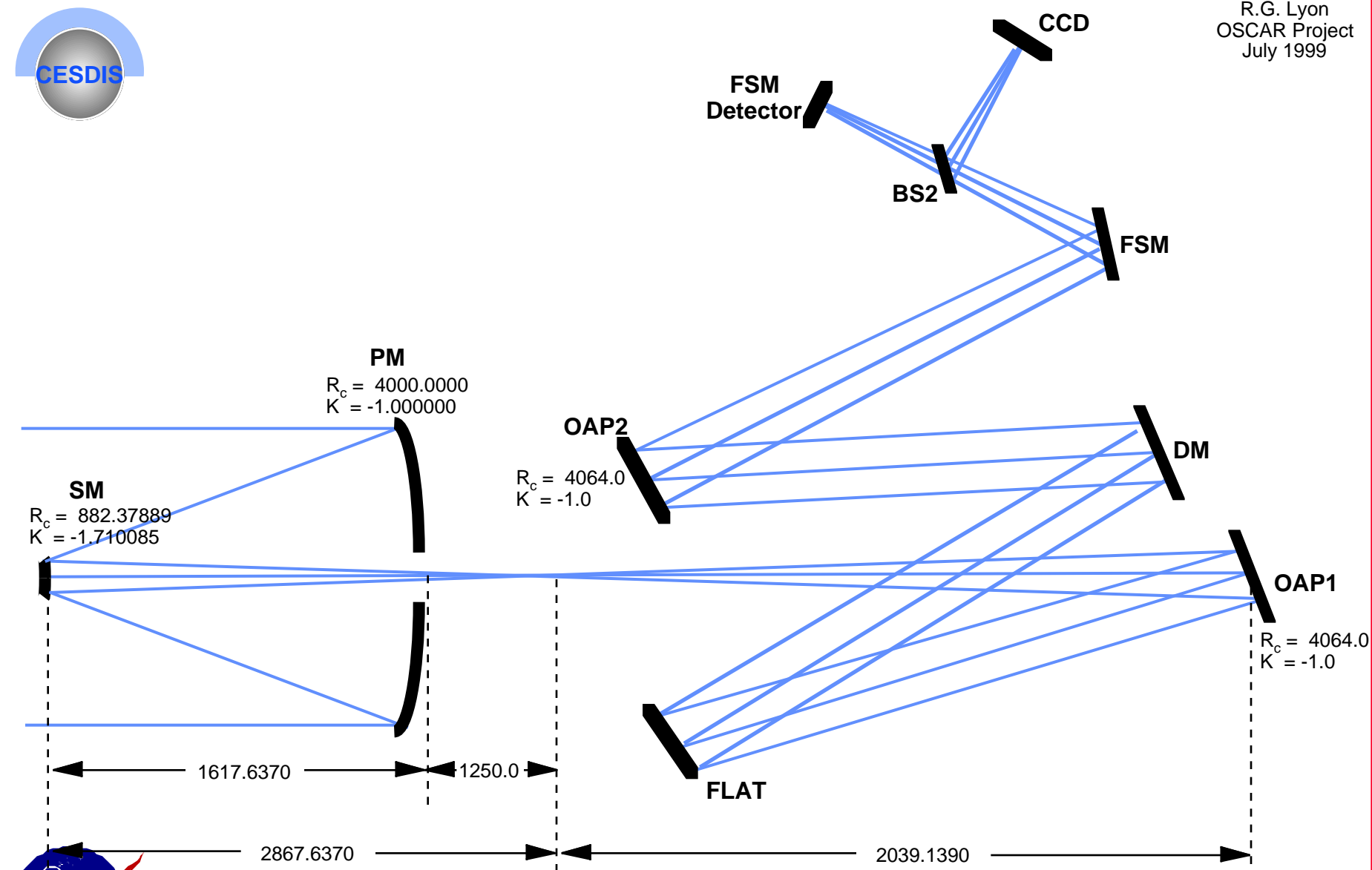
- (LEO) ***Lyon's Electro-Optical Modeling and Analysis Software***
 - Multiple plane *diffraction*, Fresnel, Fraunhofer and rigorous Angular Spectrum.
 - *Segmented* apertures and *deformable* mirrors, influence functions, range limits, clamped and floating actuator models.
 - Full- and sub-aperture *Zernike* polynomials.
 - power law *random surfaces*.
 - White noise, harmonic and low frequency *jitter models*.
 - *Detector effects*, MTF, charge transfer efficiency, pixelization effects, quantization error, dynamic range effects, quantum efficiency.
 - Gaussian and Poisson noise models.
 - System *radiometry* spectral filter functions, optics transmission.
 - *Coronagraph* capability with assortment of masks and Lyot stops.
 - *Scattering*, Surface Scatter, Diamond Turning, Atmosphere
 - *Scene Modeling* Fractal landmass, cloud and water models from LEO/ GEO and with *scan mirror* options.
 - Fourier Transform based *Imaging Interferometer* model.
 - *Inhomogenous wave propagation* finite element model (in progress)
 - Shack-Hartmann sensor model (in progress).



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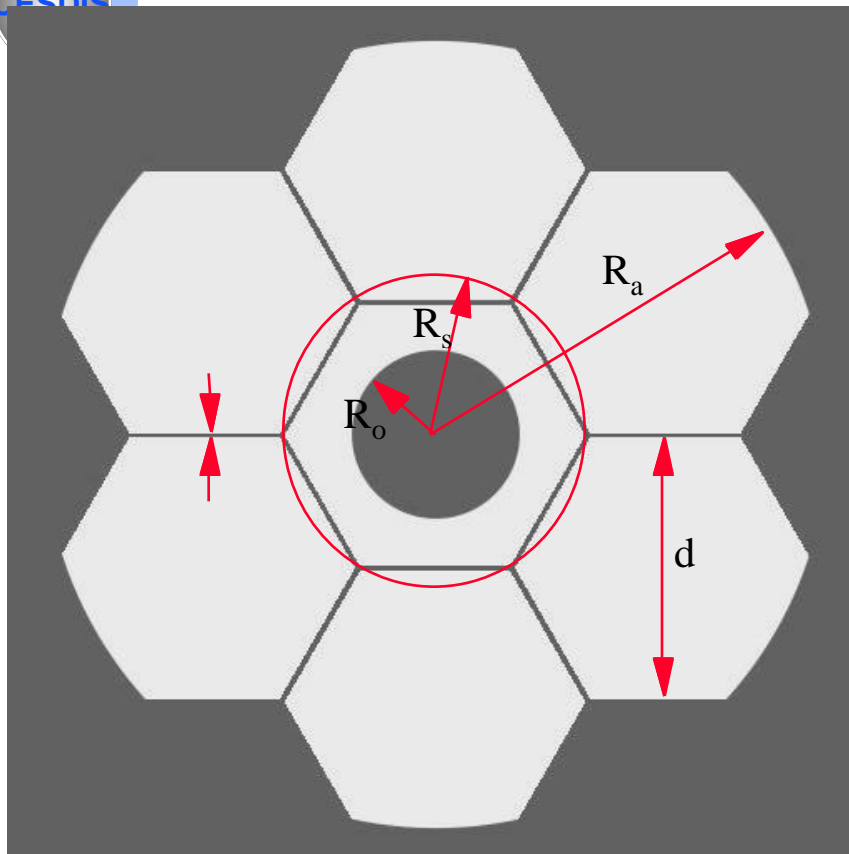


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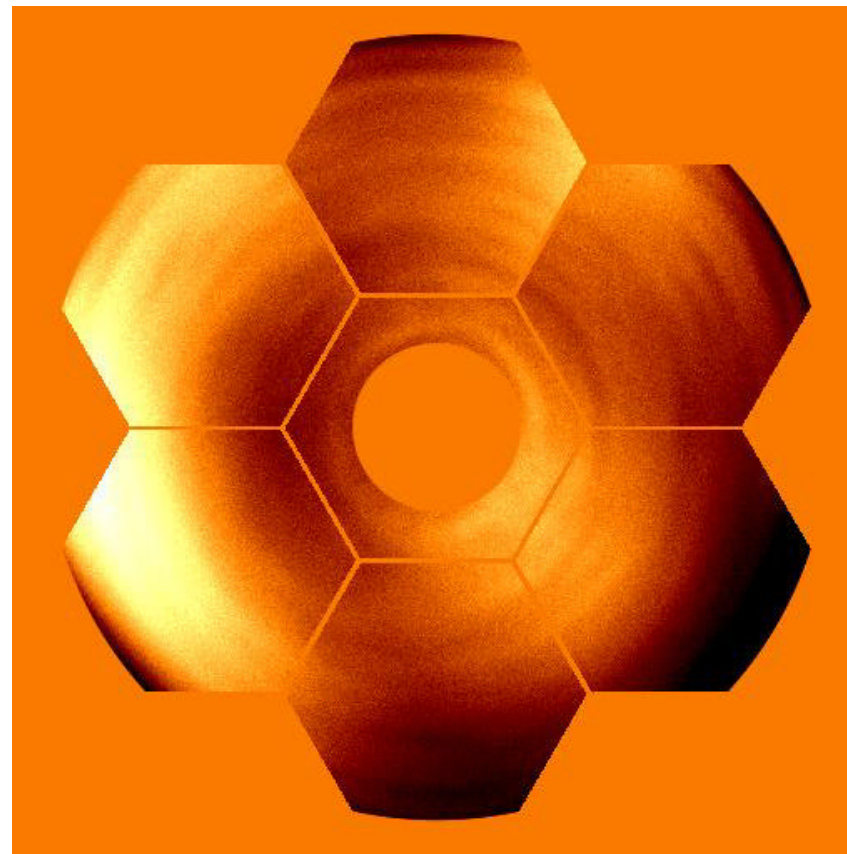
Optical Schematic

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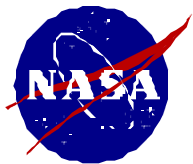
DCATT Aperture Function Geometry

$d = 300.000 \text{ mm.}, \quad = 6.000 \text{ mm.}$
 $R_a = 451.690 \text{ mm.}, \quad R_s = 173.205 \text{ mm.}$
 $R_o = 96.589 \text{ mm.}$



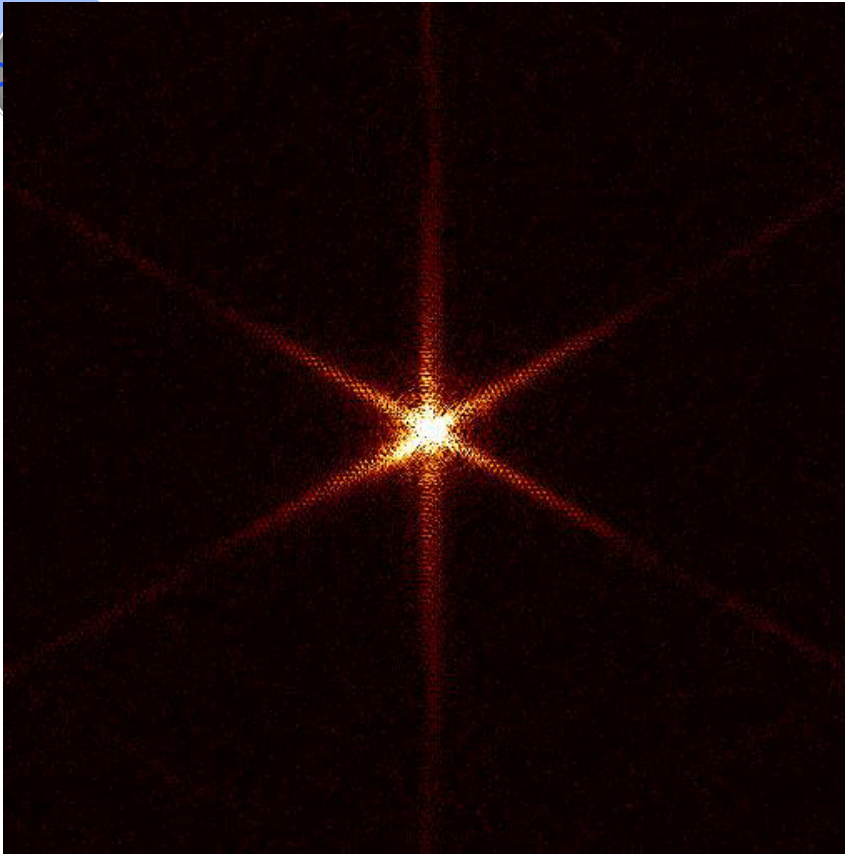
Sample DCATT Phase Function

$= 0.285$
 $\text{max} = 0.847$
 $\text{min} = -1.327$



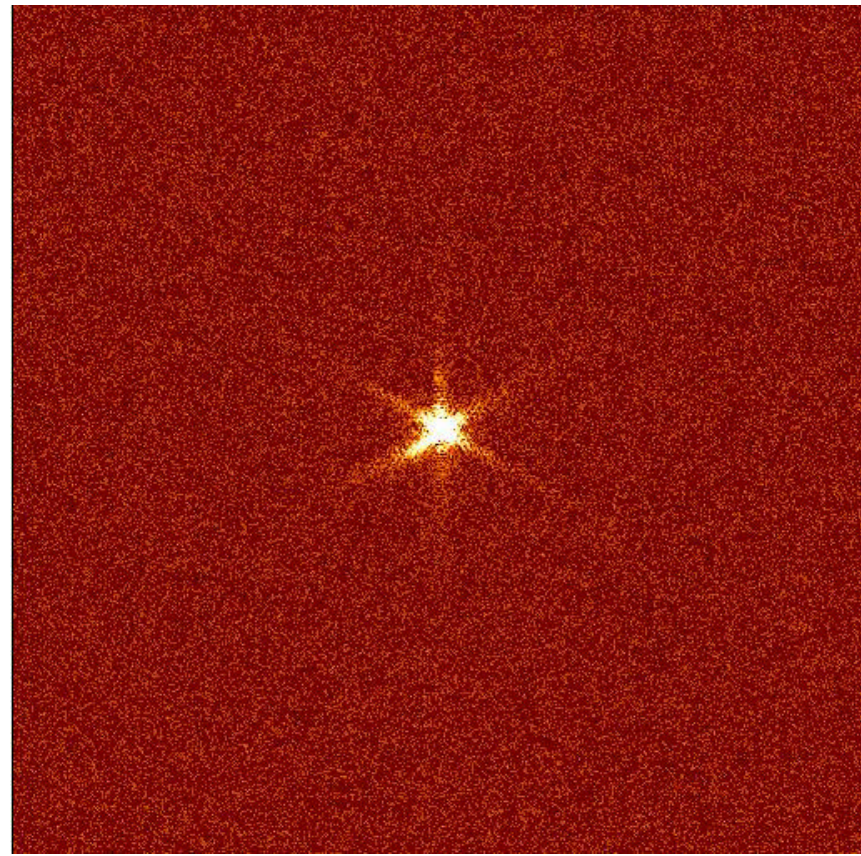
Simulated Pupil and Phase Function

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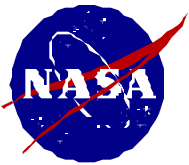
DCATT Simulated Sample PSF

Diffraction only
 micro-roughness = Y
 polish marks = Y
 scatter = N
 jitter = N



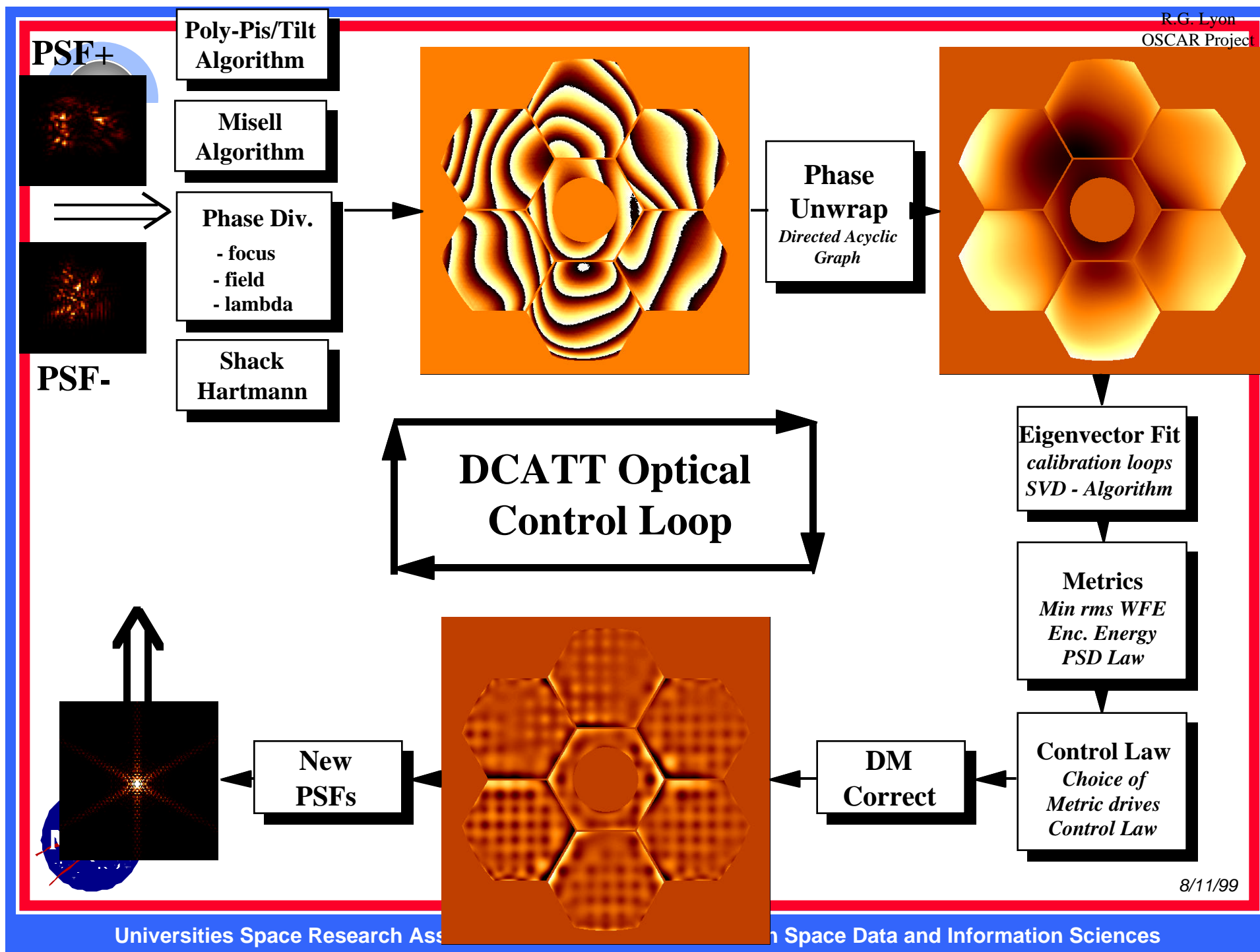
DCATT Simulated Sample PRF

12bit = 4096
 fullwell = 80,000 e
 readnoise = 13 e rms
 shot noise = Y
 detectors = 9 μ m



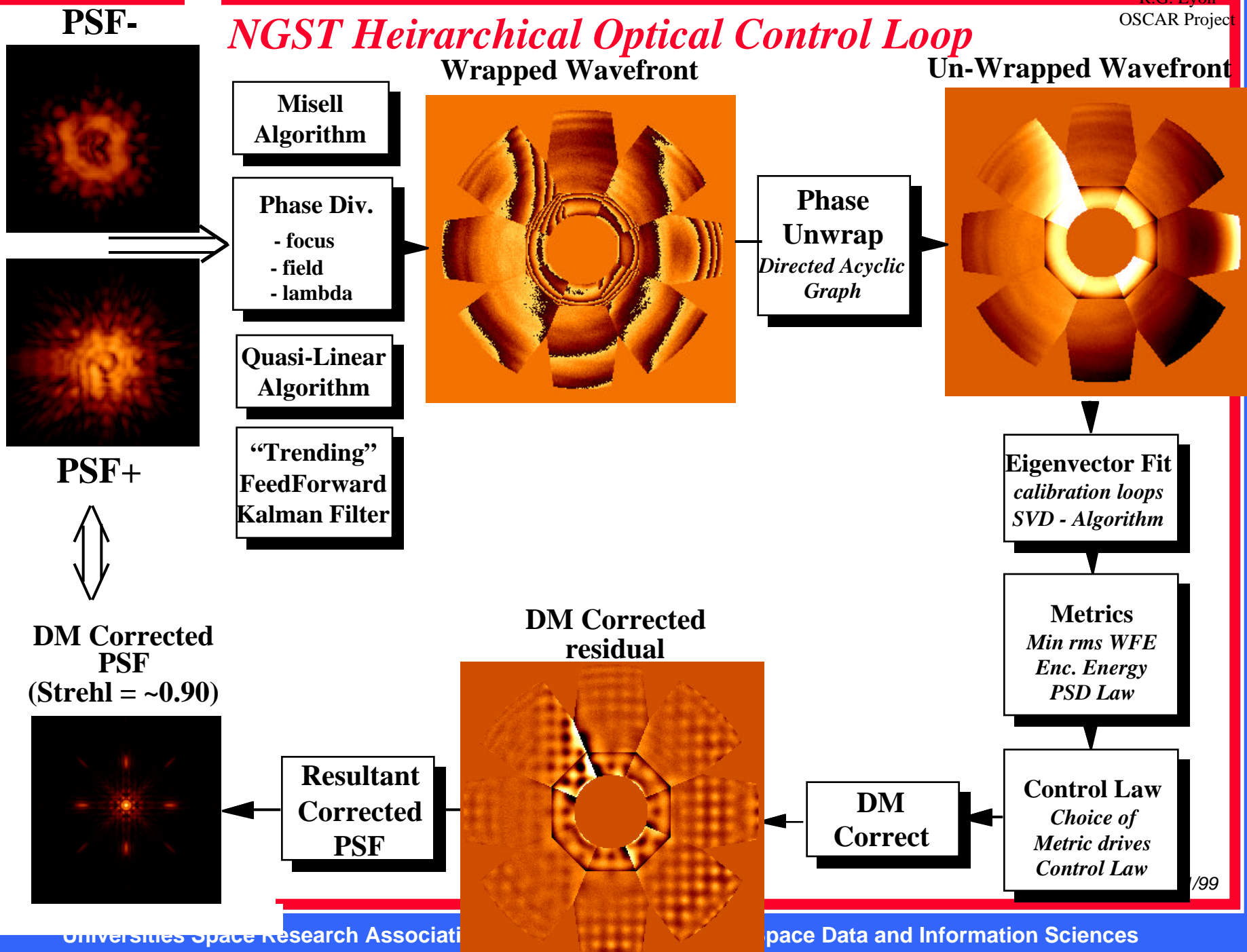
Simulated Point Spread Function and Point Response Function

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NGST Heirarchical Optical Control Loop





Phase Retrieval Problem Statement

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- From observed *Point Response Functions* find wavefront error (WFE) ϕ
- WFE gives optical surface structure.
- *Point Spread Function* is modulus squared of 2D Fourier Transform of complex pupil function. Image = convolution of PSF with object.

$$PSF(x, y; \alpha, \lambda) = \left| \frac{1}{\lambda F} \int \int A(u, v) e^{i\phi(u, v; \alpha)} e^{-i2\pi(f_x u + f_y v)} du dv \right|^2$$

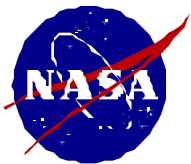
$$f_x = \frac{-x}{\lambda F} \quad \text{and} \quad f_y = \frac{-y}{\lambda F}$$

- The PRF is PSF integrated across spectral passband, convolved with detector spatial response and sampled.

$$PRF(x, y; \alpha) = \int PSF(x, y; \alpha, \lambda) S(\lambda) d\lambda ** \text{rect}\left(\frac{x}{X}\right) \text{rect}\left(\frac{y}{Y}\right)$$

- What's actually measured is given by:

$$M(x, y; \alpha, flux, A, B, C) = flux * PRF(x, y; \alpha) + A * x + B * y + C + \eta(x, y)$$



- Requires complex nonlinear iterative algorithms to find (u,v) from M(x,y, , flux,A,B,C)

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Pupil Plane

FFT⁻¹

Focal Plane

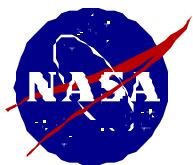
$$P_n(x, y) = |P_n(x, y)| e^{i\phi(x, y)}$$

$$\tilde{P}(f_x, f_y) = \left\{ \beta \sqrt{PSF(f_x, f_y)} + (1 - \beta) \right\} |\tilde{P}(f_x, f_y)| e^{i\theta(f_x, f_y)}$$

$$P_n(x, y) = A_0(x, y) \frac{|P_n(x, y)| e^{i\phi(x, y)}}{|P_n(x, y)|}$$

$$\tilde{P}(f_x, f_y) = |\tilde{P}(f_x, f_y)| e^{i\theta(f_x, f_y)}$$

FFT



Modified Iterative Transform Algorithm

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Add
Diversity

$$\phi_1 = \phi + \delta\phi_1$$
$$P_1 = A_1 e^{i\phi_1}$$

$$\phi_2 = \phi + \delta\phi_2$$
$$P_2 = A_2 e^{i\phi_2}$$

$$\phi_3 = \phi + \delta\phi_3$$
$$P_3 = A_3 e^{i\phi_3}$$

$$\phi_4 = \phi + \delta\phi_4$$
$$P_4 = A_4 e^{i\phi_4}$$

Propagate

FFT

FFT

FFT

FFT

Apply
Observed
PSFs

$$\tilde{P}_1 = \sqrt{PSF_1} e^{i\theta_1}$$

$$\tilde{P}_2 = \sqrt{PSF_2} e^{i\theta_2}$$

$$\tilde{P}_3 = \sqrt{PSF_3} e^{i\theta_3}$$

$$\tilde{P}_4 = \sqrt{PSF_4} e^{i\theta_4}$$

Inverse
Propagate

FFT⁻¹

FFT⁻¹

FFT⁻¹

FFT⁻¹

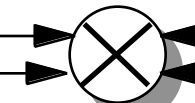
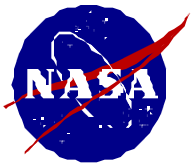
Mix
Phases

$$P_1 = A_1 e^{i\phi_1}$$

$$P_2 = A_2 e^{i\phi_2}$$

$$P_3 = A_3 e^{i\phi_3}$$

$$P_4 = A_4 e^{i\phi_4}$$



$$\phi_{j+1}(x,y)$$

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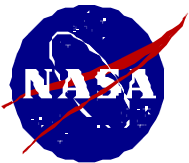
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Control Precision vs. rms WFE

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- Utilized LEO to generate 400 PSFs, 4 each at 100 realizations of WFE from 0 - 2.5λ rms.
 - Full aperture Zernikes, Sub-aperture Zernikes, segment piston/tip/tilt
 - finite spectral bandpass ($\Delta\lambda = 0.6328$, $\Delta\lambda = 10\text{nm}$)
 - detector and actuator effects.
- Passed each through:
 - 4 PSF Misell,
 - phase unwrapping,
 - DM control, DM control with limits,
 - DM+PM control.
- Tabulated output precisions vs. rms WFE for each case.
- WFS precision is $\lambda/23 \pm \lambda/52$ rms
- Control with range limited DM+PM $\sim \lambda/10$
- RSS of Sensing and Control errors is $\sim \lambda/9$

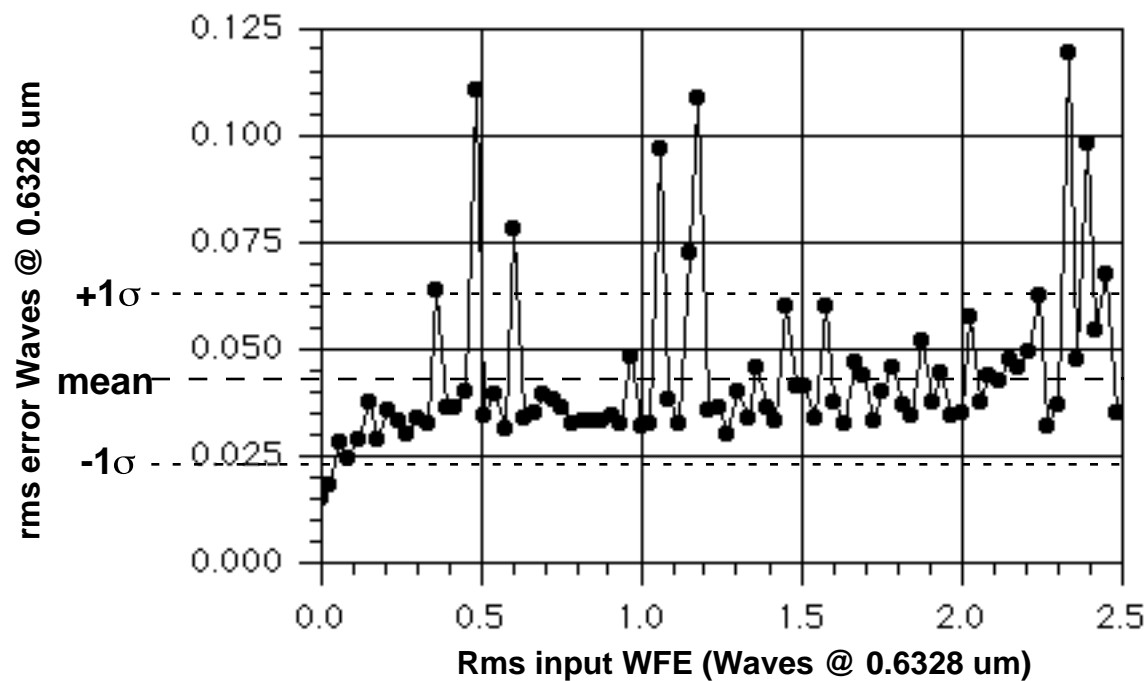


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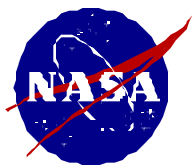


Wavefront Sensing Precision

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- Wavefront sensing precision is $\lambda/23 \pm \lambda/52$ over range $\{0 - 2.5\lambda\}$.
- Anomalies caused by phase unwrapping problems.



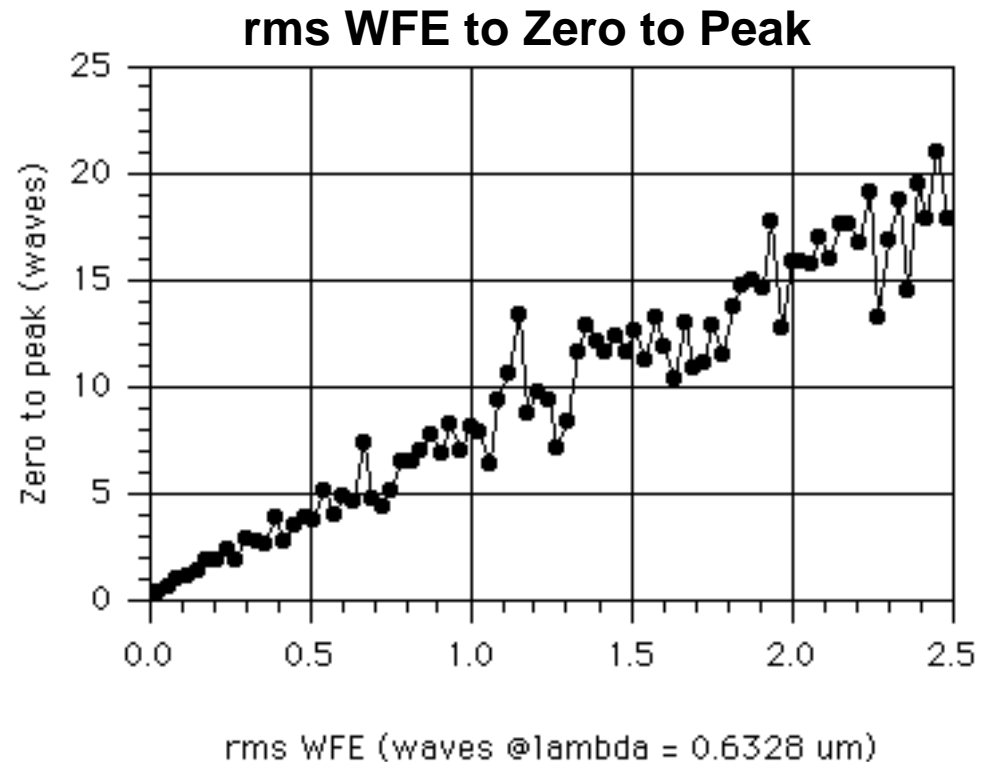
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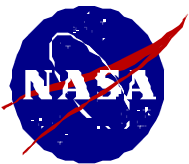
Phase Unwrapping

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slope ~7.5 waves/rms wave
phase unwrap for > 0.15 waves rms



- Number of Phase Unwrapping Methods Explored
- Problems occur for:
 - Large slopes => unresolved edges
 - Jitter => “*Branch Points*”
 - Low SNR => poor “fringe edge”
- Need diagnostic to tell *if needed* and *if failed*

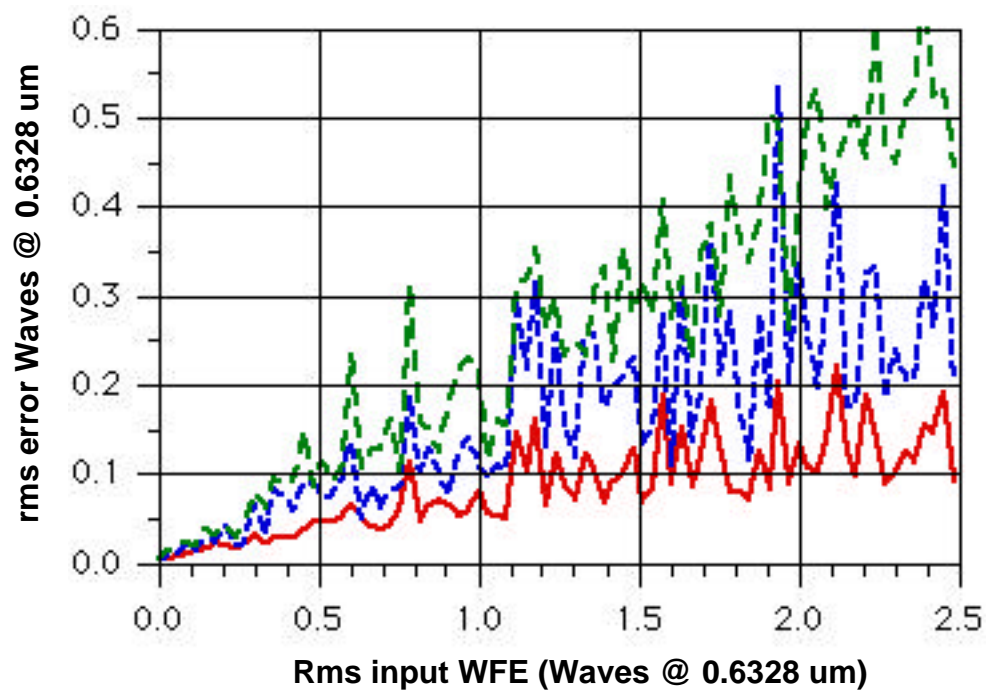


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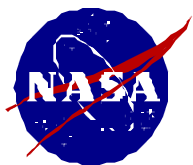
DM and PM Control vs rms WFE

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- Over error budgeted range
 {0 - 1λ rms}
- **DM+PM controls $< \lambda/10$**
- Error grows linearly with rms WFE

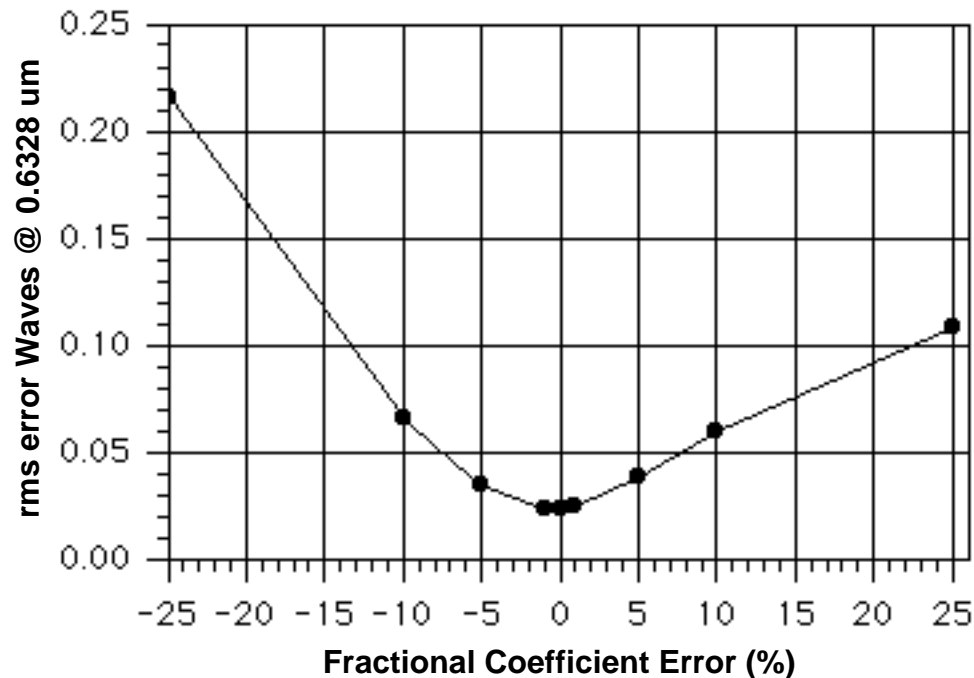
— DM+PM Control, no range limits
- - - DM+PM Control, with range limits
- - - DM Control only, with range limits



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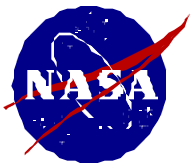
Influence Function Sensitivity



- Influence function model for DM from Dave Redding:

$$R(r) = e^{-Ar} \cos(Ar)$$

- “A” varied over +/- 25% from nominal
- Input WFE = 0.25 waves rms (lambda = 0.6328 um)





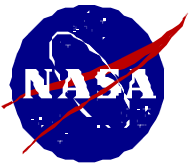
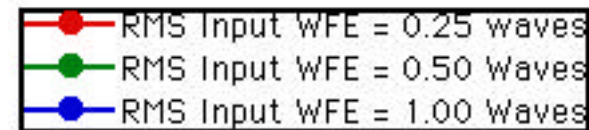
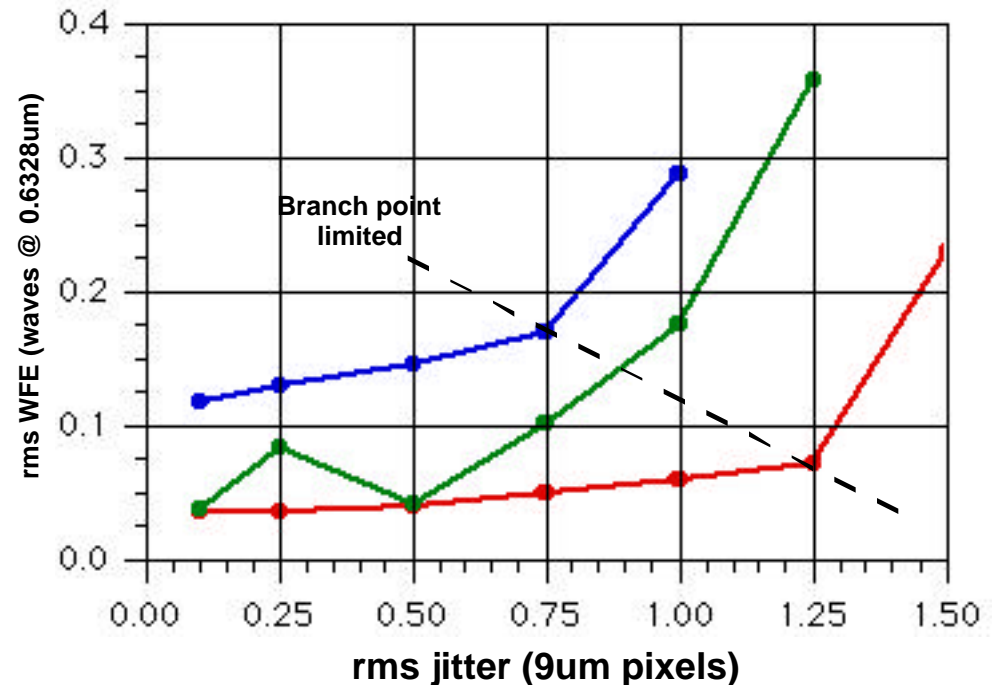
WFS Precision due to Jitter

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- Jitter model is non-deterministic.
- Low-pass filter on OTF:

$$\langle H(f_x, f_y) \rangle = e^{-\left(\sigma_x^2 f_x^2 + \sigma_y^2 f_y^2\right)}$$

- x-rms \Leftrightarrow y-rms
- Hi-FI models possible.
- effect is generation of “unphysical” branch points.
- Branch points cause errors in phase unwrapping.
- Useful as diagnostic ?
- Number of branch points imply severity of jitter.
- Jitter *deconvolution* possible ?
- Metric would be residual branch points.

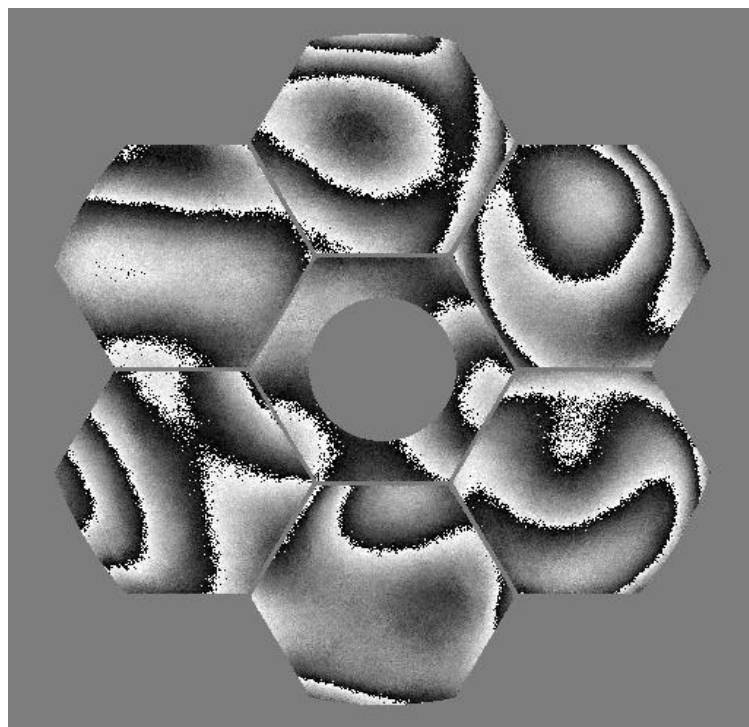


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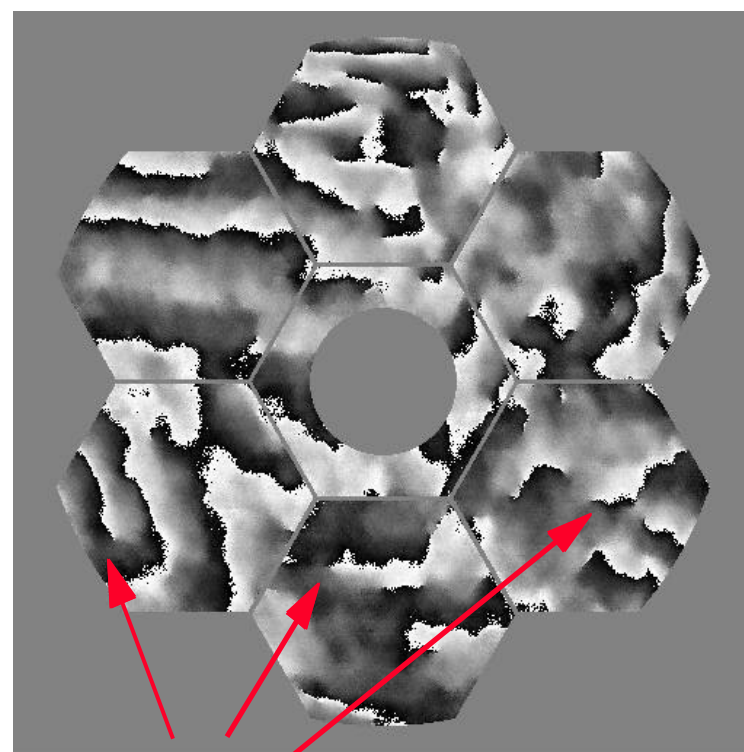


Jitter Induced Branch Points

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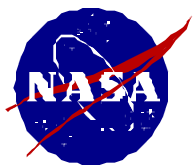


WFE = 1.00 waves rms
Jitter = .1 pixel rms (9 μ m)



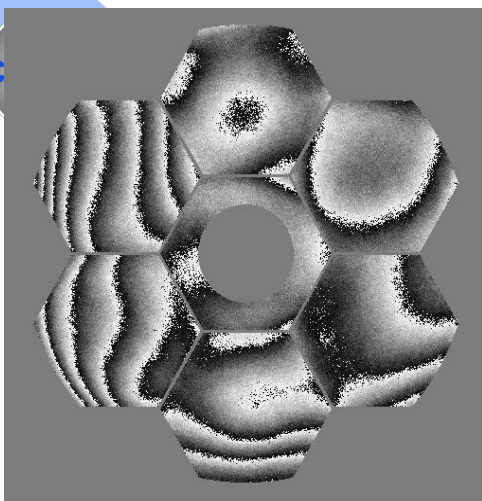
Jitter Induced
Branch Points

WFE = 1.00 waves rms
Jitter = 1 pixel rms (9 μ m)

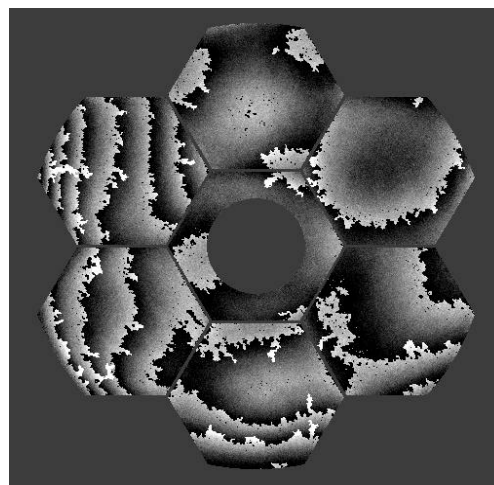


Allowable Jitter strongly correlated with WFE.
Jitter makes phase unwrapping tough.

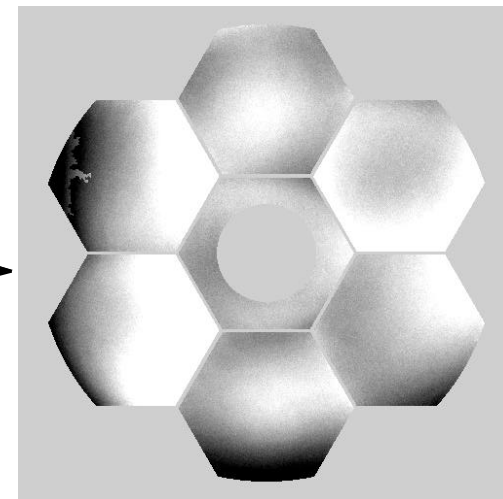
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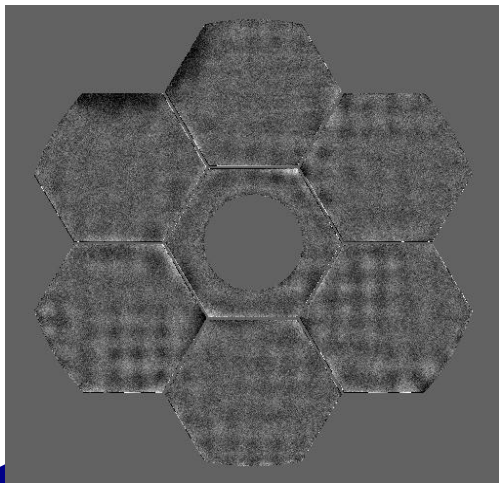
4 PSF Misell Algorithm Solution
Optical, Detector effects
~100 iterations, $\lambda=6328\text{um}$ $\text{dl}=100\text{ Ang}$



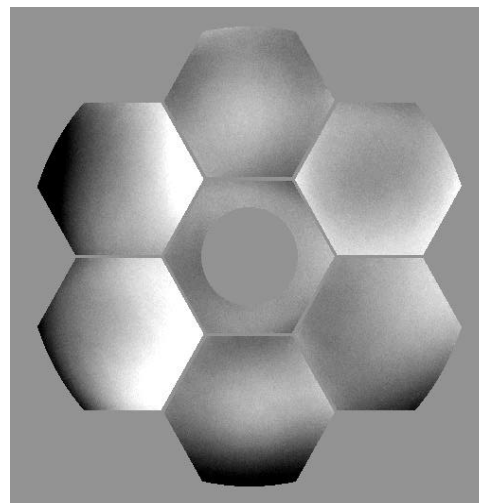
Phase Unwrap Preprocessor
(lowers number of regions)



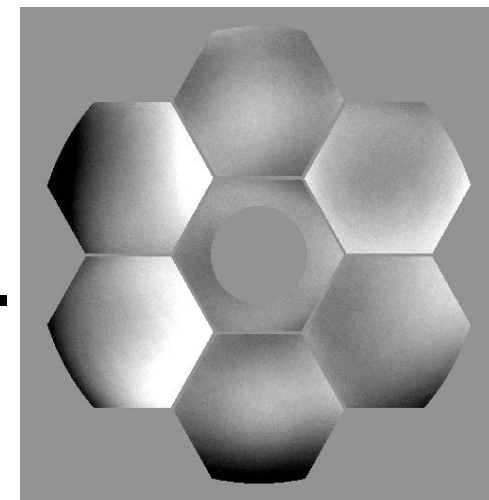
Swipe 1 of DAG
phase unwrapping



Residual WFE
Both DM and PM Control
 $\text{rms}=\lambda/12, \text{max-min}=1.3\lambda$

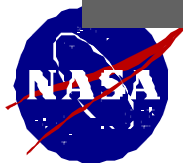


Best fit Wavefront
Both DM and PM Control
 $\text{min}\{\text{rms}\}$ metric



Swipe 2 of DAG
phase unwrapping

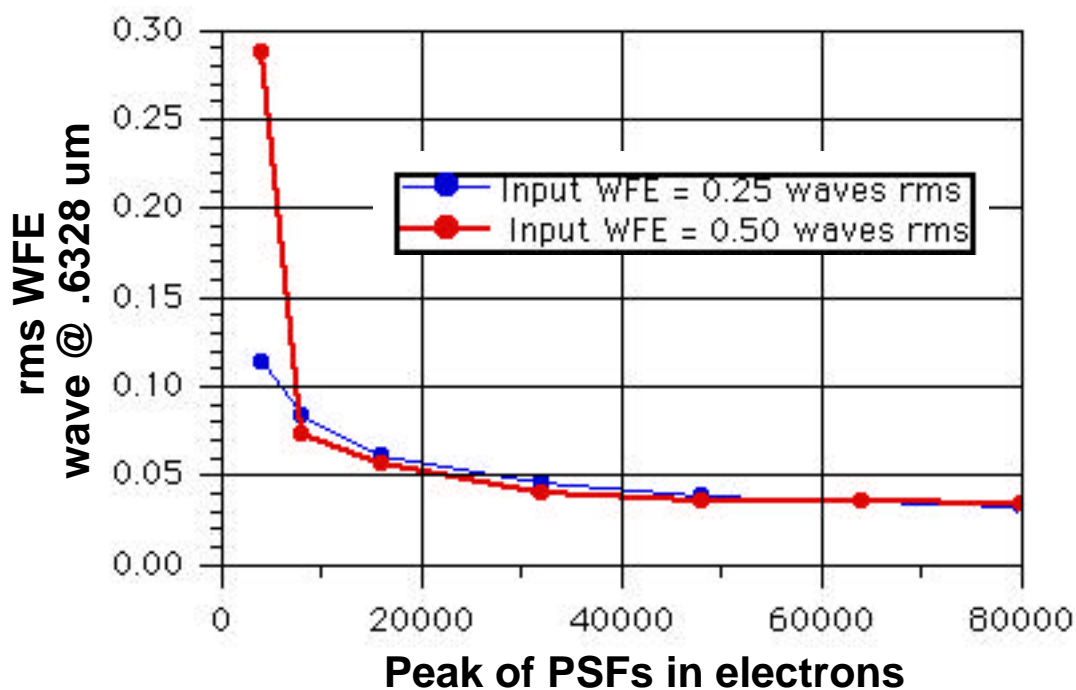
8/11/99



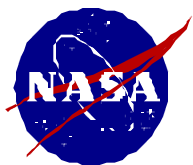


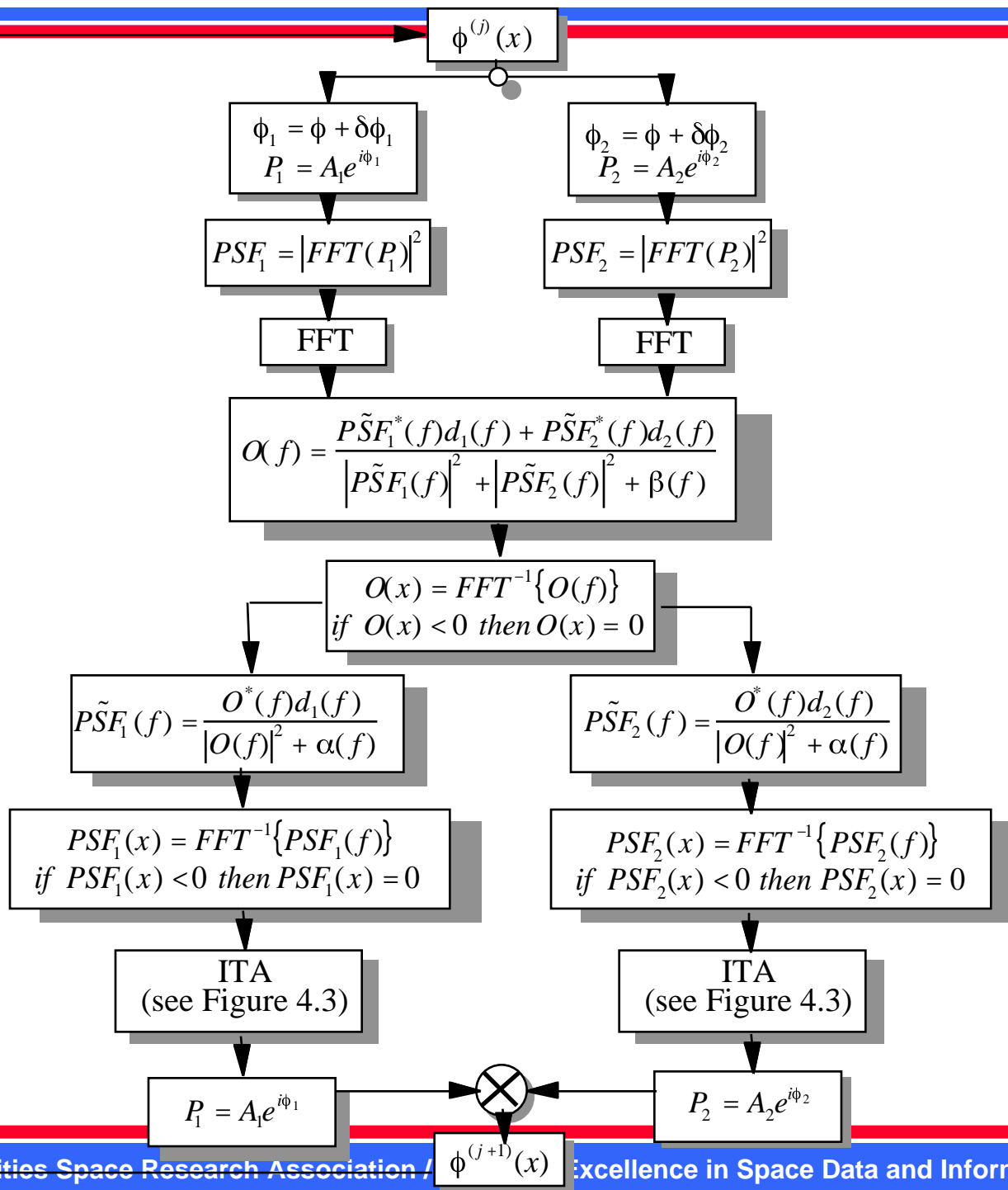
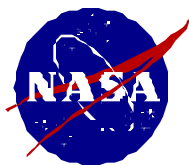
WFS Precision vs. SNR

- Utilized LEO to generate sequence of different SNR PSFs,
- 7 sets at $\sigma=0.25\lambda$ rms, and 7 sets at $\sigma=0.25\lambda$ rms, 4 PSFs/ realization.
- Passed each through 4 PSF Misell with phase unwrapping.
- Tabulated output precisions vs. SNR
- RMS output error was $< \lambda/20 > 20,000$ electrons.
- Errors due to: phase edge loss and increased phase noise



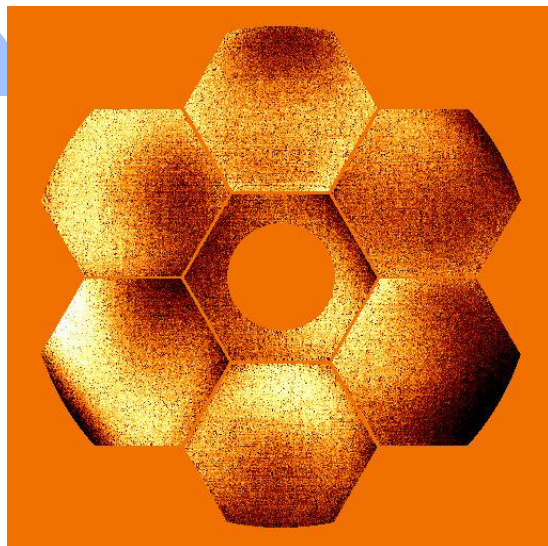
KAF1600 chip
readnoise 13e rms.
80,000e full well.
12 bit quantization.
9 micron pixels



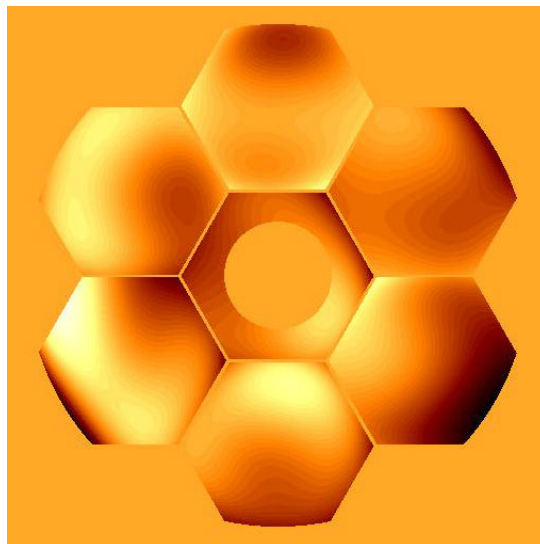




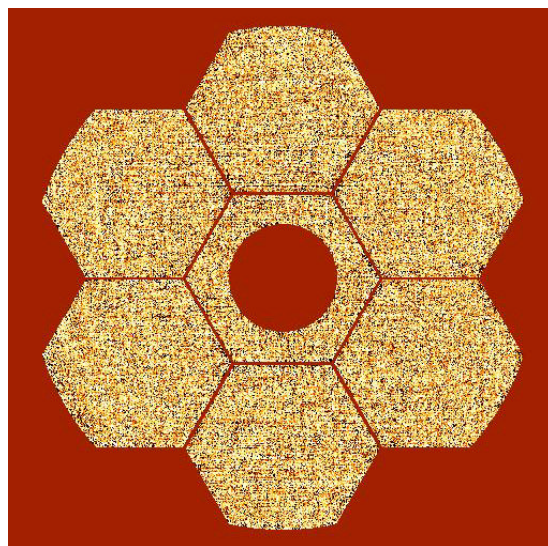
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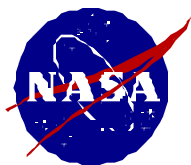
**Phase Diverse
Recovered Phase**
 0.320λ rms



True Phase
 0.273λ rms



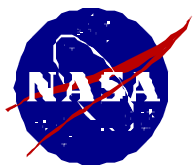
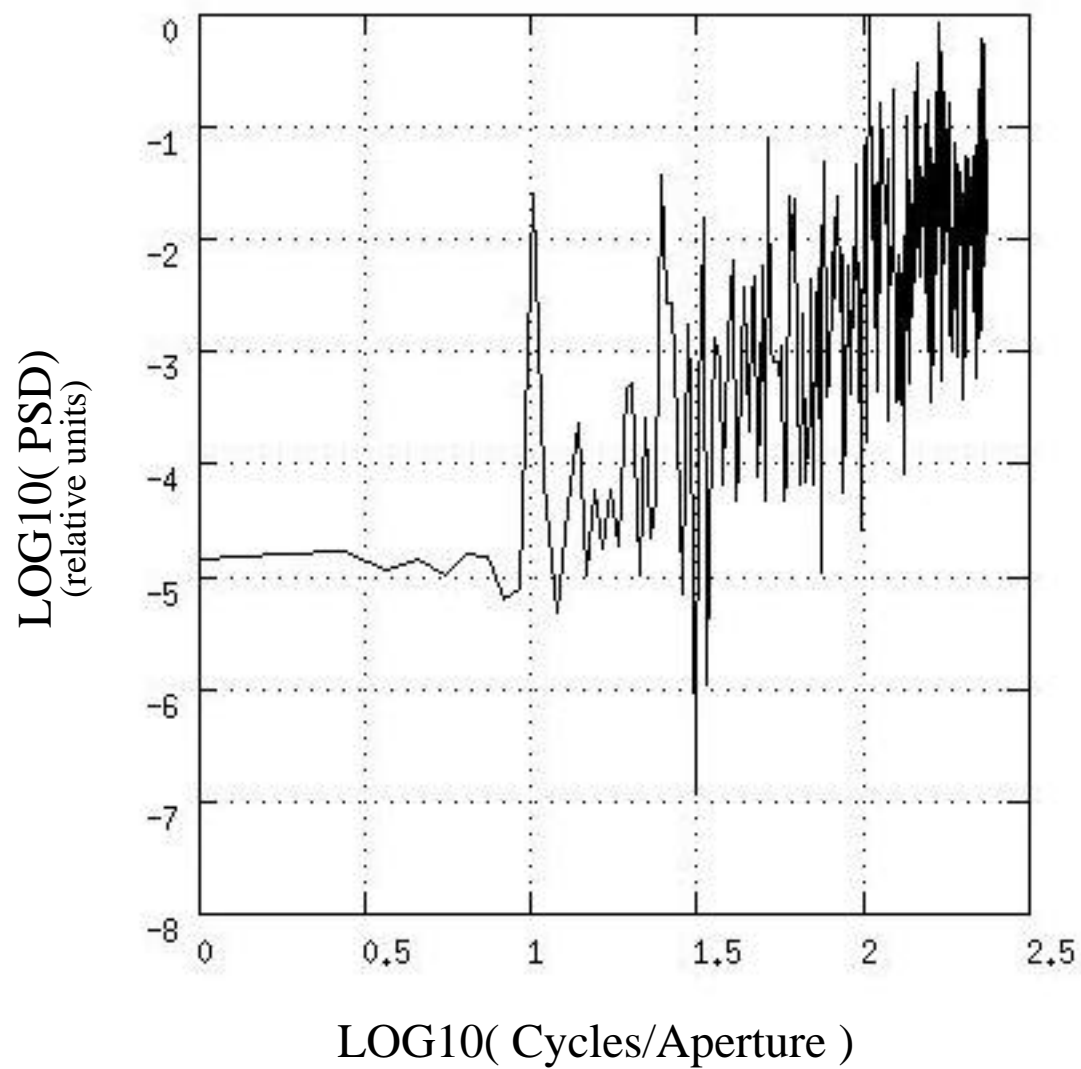
Difference Phase
 0.167λ rms



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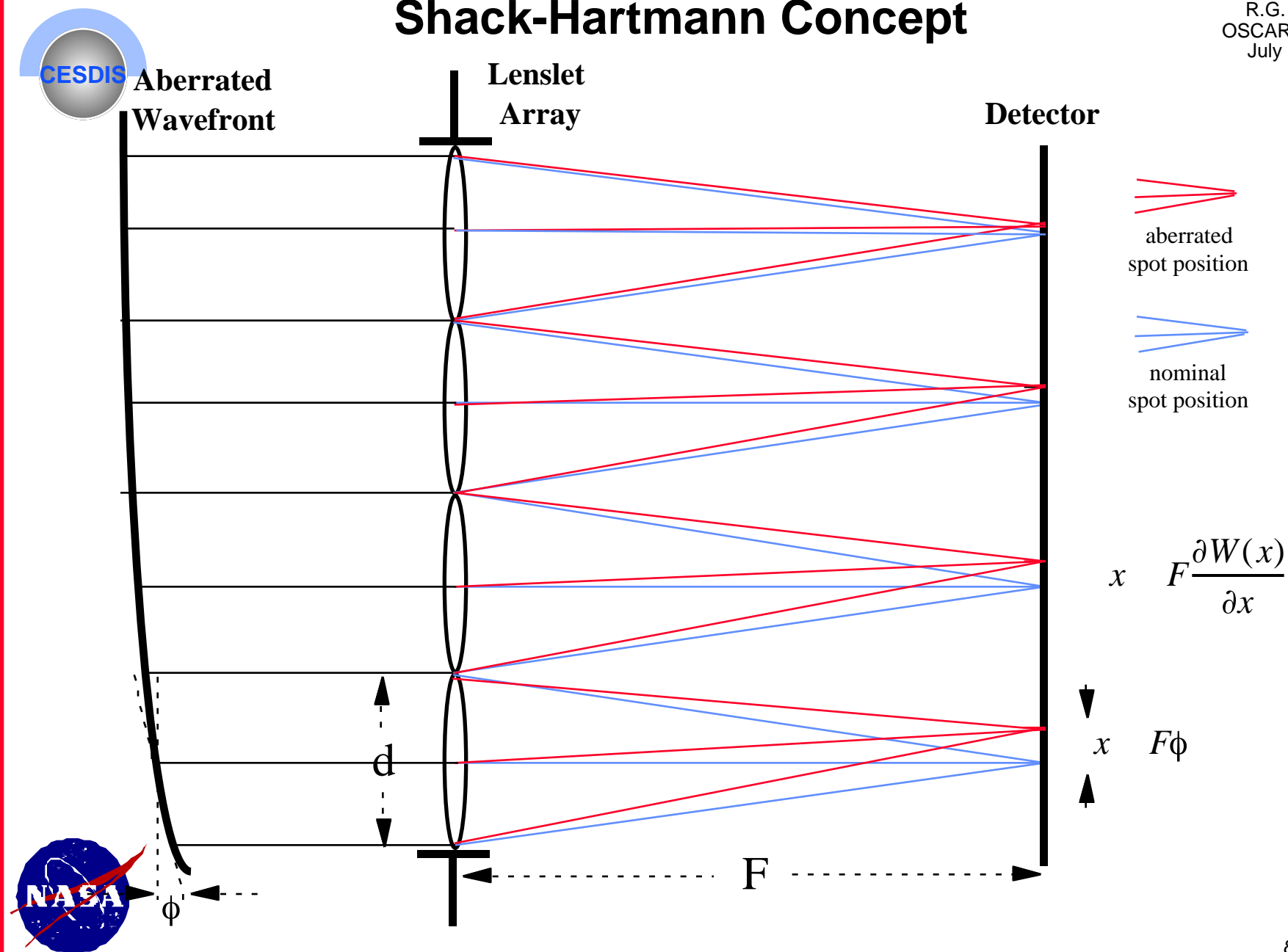
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Shack-Hartmann Concept

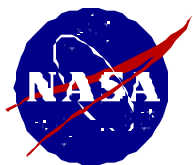
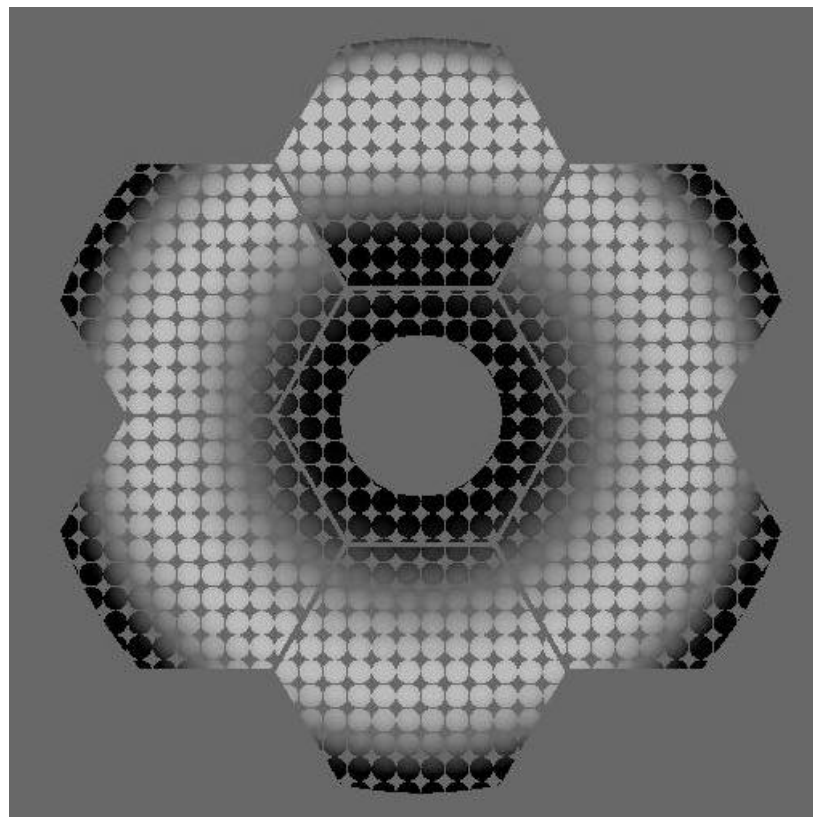
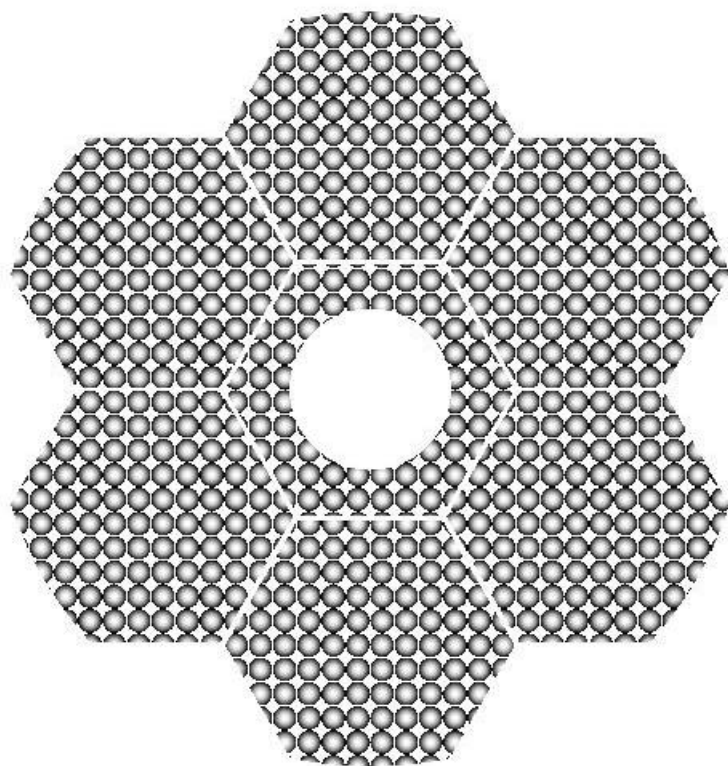
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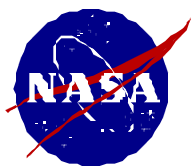
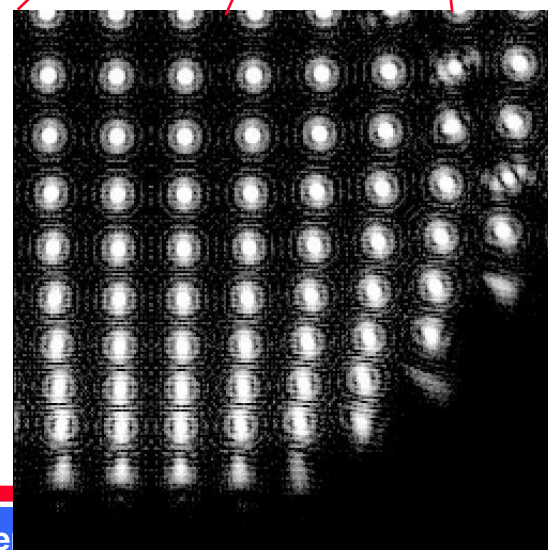
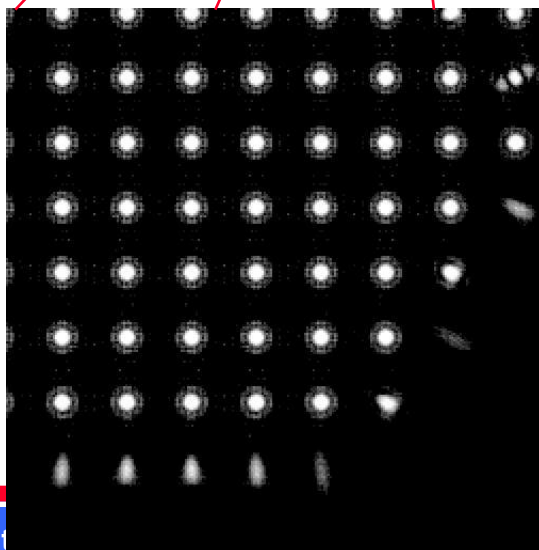
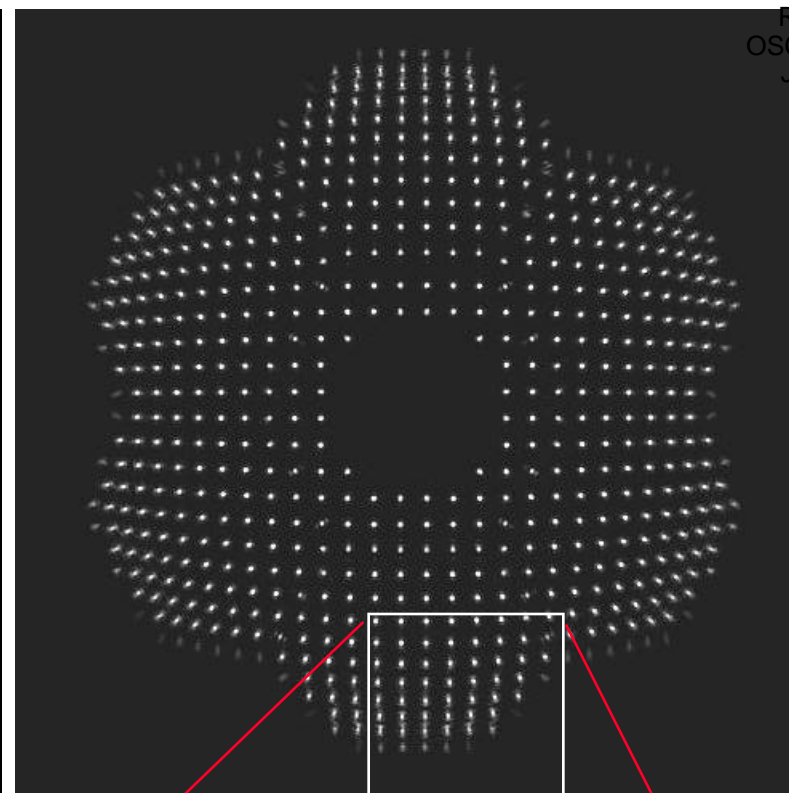
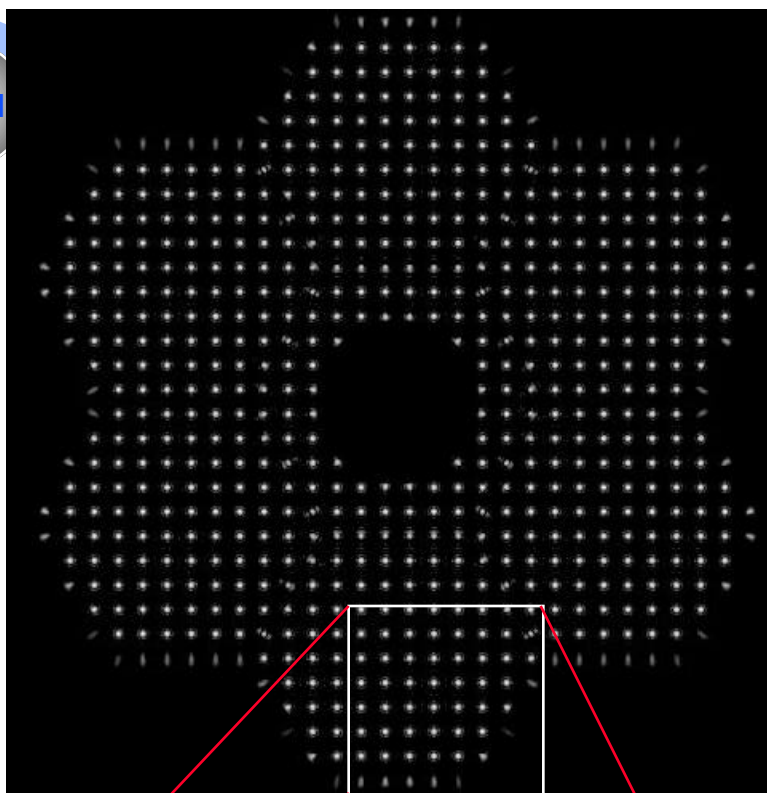
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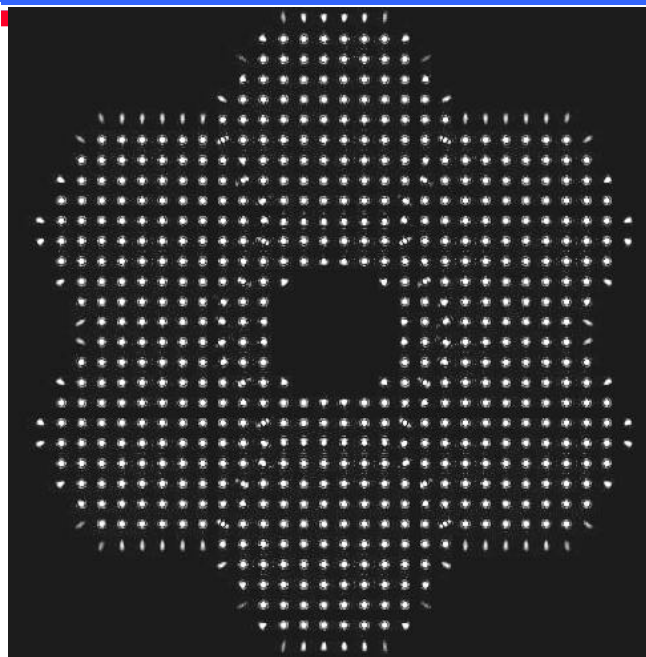
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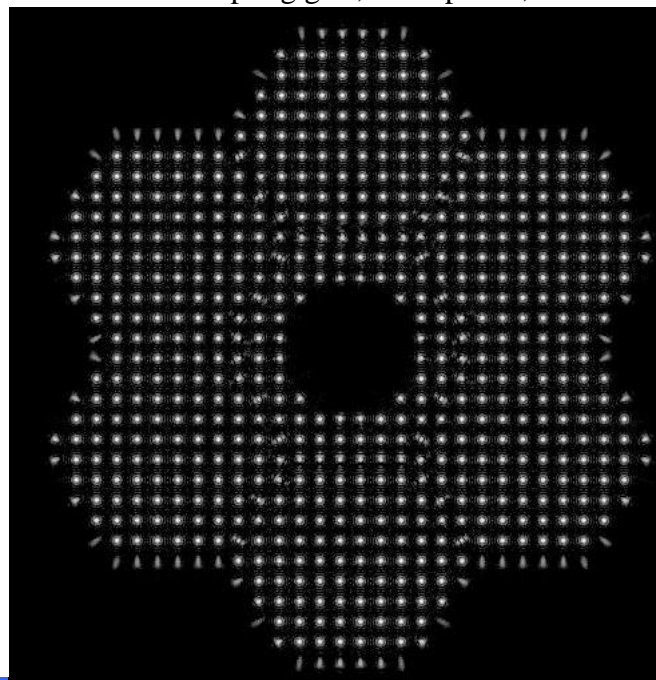


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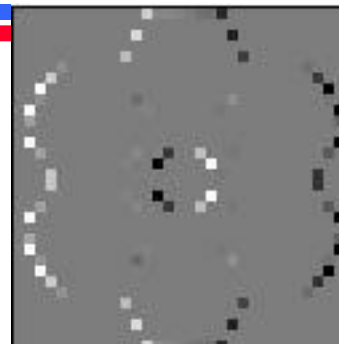


32 x 32 lenslets

1024 x 1024 sampling grid, 9 um pixels, $\lambda = 0.6328$



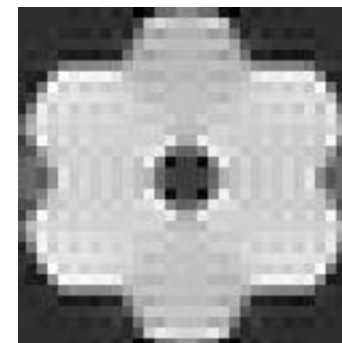
$$\frac{\partial W(x, y)}{\partial x}$$



$$\frac{\partial W(x, y)}{\partial y}$$



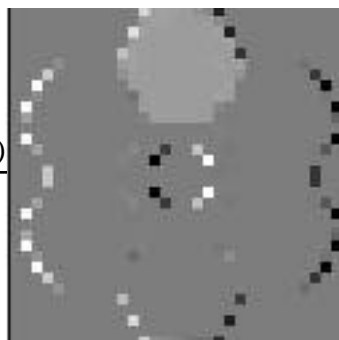
$\phi(x, y)$



Null Case

$$\tilde{\phi}(f_x, f_y) = \frac{-i}{2\pi} \frac{f_x FT \frac{\partial W(x, y)}{\partial x} + f_y FT \frac{\partial W(x, y)}{\partial y}}{f_x^2 + f_y^2}$$

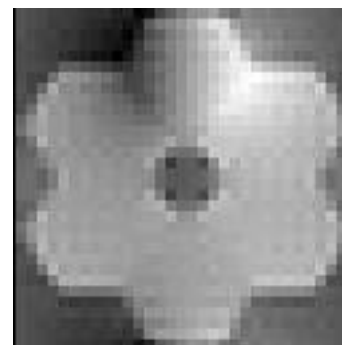
$$\frac{\partial W(x, y)}{\partial x}$$



$$\frac{\partial W(x, y)}{\partial y}$$



$\phi(x, y)$



Segment Tilt

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Major Results of models for DCATT to Date

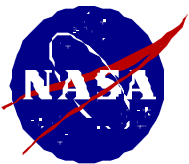
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Simulations show error budget can be met for DCATT Fine Figure Control.

Over budgeted range 0 - 1 λ rms input WFE for DCATT

| | |
|---|--|
| WFS DM+PM Control Jitter SNR | $\sim \lambda/23$ $< \lambda/10$ $< \lambda/8$ (0.25 rms jitter) $\sim \lambda/10$ (Fullwell > 20000, SNR > 62) |
| σ (RSS) σ (error budget) | $\sim \lambda/5.2$ $\lambda/4.43$ |

- Doesn't include stray light, diamond turning or turbulence.
- WFS Precision strongly correlated with Jitter.
- Phase unwrapping needs to be addressed in more detail.
- SNR doesn't appear to be a problem.
- Phase Retrieval can be used over much large input WFE range.



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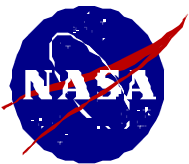
Summary

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- Developed Hi-Fi model of segmented optical system.
- Developed model and simulated active optical control loop.
- Developed model and simulated Phase Retrieval.
- Developed model and simulated Shack-Hartmann.
- Studied effects of {jitter, SNR, Phase Retrieval, control...}
 - developed on MasPar MP2, in a superset of “C”.
 - currently being converted to “C” with MPI.
- Still must perform studies with Shack-Hartmann
- Compare Phase Retr. vs Shack-Hartmann, other methods ?
- 1st Report available on <http://jansky.gsfc.nasa.gov/OSCAR>

Future Work

- “Quasi-Linear” WFS, In-situ science obs WFS.
- In-situ system calibration (aka system identification).
- Hi-density actuators.
- Verify models and algorithms with “real” data.



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